

Electromagnetic Signals from Planetary Collisions

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Abstract. We investigate the electromagnetic signals accompanied with planetary collisions and their event rate, and explore the possibility of directly detecting such events. A typical Earth–Jupiter collision would give rise to a prompt EUV-soft-X-ray flash lasting for hours and a bright IR afterglow lasting for thousands of years. With the current and forthcoming observational technology and facilities, some of these collisional flashes or the post-collision remnants could be discovered.

INTRODUCTION

More than 100 extra-solar planets have been detected. At the same time, our understanding of astrophysical phenomena has been greatly boosted through studying cataclysmic transient events such as supernovae, X-ray bursts, and gamma-ray bursts. Another type of electromagnetic transient events that arises from collisions of extra-solar planets has been long predicted in the context of planet formation[1]. Recently we discussed the possible electromagnetic signals accompanying such collisional events[2]. Discovering such events would undoubtedly have profound implications of understanding the formation rate, dynamical instability, as well as internal composition and structure of extrasolar planets.

ELECTROMAGNETIC SIGNALS: THREE STAGES

Generally one can categorize the collision-induced signals into three stages, defined by three characteristic time scales. Below we will take a head-on collision between a Jovian planet and an Earth-size planet as an example. A schematic lightcurve is presented in Figure 1.

Stage 1: Prompt EUV-Soft-X-ray Flash

Assuming zero velocity at infinity, the total energy of the collision is about 6×10^{40} erg. Upon impact, a reverse shock propagates into the impactor (i.e. the Earth-size planet), and the shock crossing time scale is ~ 10 minutes. This defines the rising timescale of the collision-induced electromagnetic flash. The energy deposition rate during this stage is $\sim 10^{38}$ erg s $^{-1}$, much greater than Jupiter’s Eddington luminosity.

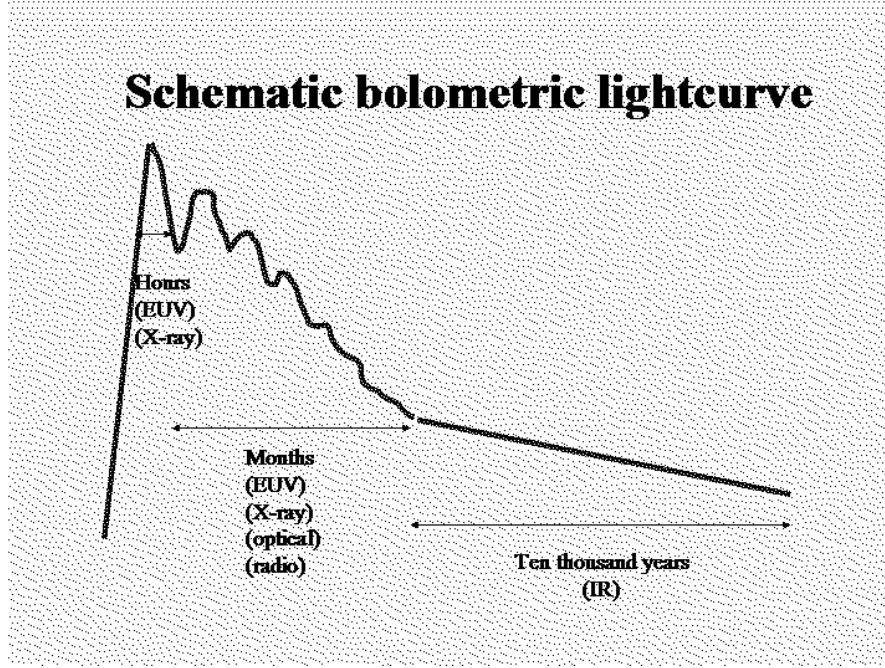


FIGURE 1. A schematic bolometric lightcurve for a Jupiter-Earth collision event. Three stages are highlighted: (1) a prompt EUV-soft-X-ray flash, characterized by a sharp rise and milder decay lasting for hours; (2) a spin-modulated decaying lightcurve lasting for about a month, which could be visible in the EUV, X-ray, optical and radio bands; (3) a long-term IR warm afterglow lasting for thousands of years.

A likely picture is that the prompt heat generated upon collision would dissociate the molecules and ionize the atoms within a short period of time, and the emission quickly becomes Eddington-limited. After the peak, the lightcurve decays mildly as the deceleration of the impactor is still going on inside the Jovian planet. The timescale of the prompt flash can be estimated to be of order of 10 times of the rising time, i.e.,

$$\tau_1 \sim 2 \text{ hr.} \quad (1)$$

The bolometric luminosity is near Eddington, i.e. $L_{pk} \sim 5 \times 10^{34} \text{ erg s}^{-1}$, with a thermal temperature $T_{pk} \sim 1.1 \times 10^5 \text{ K}$ emitting from a hot spot with a radius comparable of the Earth radius. The peak flux is $F_v(pk) \sim 60 \mu\text{Jy} (D/10\text{kpc})^{-2}$, peaking in the EUV band. A non-thermal tail due to Comptonization would extend into the soft-X-ray band, detectable through out the Galaxy if the neutral hydrogen absorption is not important, and is even visible from some nearby galaxies. The prompt flash greatly increases the planet-to-star flux ratio, making them detectable in the optical band through photometry monitoring [$f(U, pk) \sim 0.2$, $f(V, pk) \sim 0.02$, and $f(I, pk) \sim 0.008$, where $f(v) \equiv F(v, \text{planet})/F(v, \text{star})$]. The total energy radiated during this prompt phase is a tiny fraction ($\sim 0.5\%$) of the total energy deposited. The majority of energy is stored as latent heat and radiated over a much longer time scale.

Stage 2: Spin-Modulated Decaying Phase

After the prompt phase ends (i.e. the impactor is stopped inside the giant planet), the luminosity steadily drops. The heat deposited deep inside the giant planet would excite a vigorous convective flow. The area of the hot spot gradually gets larger and larger until the whole surface reaches the same temperature. The time scale for retaining a hot spot could be estimated as

$$\tau_2 \sim 1 \text{ month.} \quad (2)$$

During this time, an observer would see some quasi-periodic signal due to the modulation of the planet spin (with a period $\lesssim 1$ day), as the hot spot enters and leaves the field of view. The modulation pattern could be visible in EUV-X-ray, or in optical through photometric monitoring, or in radio. A radio flare is expected during the vigorous convective epoch due to the enhanced dynamo activity inside the giant planet. The periodic pattern would be gradually smeared out as the hot spot boundary gradually increases.

Stage 3: Long-Term IR Afterglow

After the surface temperature becomes uniform, the giant planet keeps cooling, radiating away the majority of the energy deposited during the impact. This time scale is much longer, typically

$$\tau_3 \sim 10^3 - 10^4 \text{ yr.} \quad (3)$$

The channel of emission is mainly in IR[3]. During this epoch, the planet-to-star flux ratio in the IR band is very high. For a G2 host star, the typical I- and K-band flux contrasts are $f(\text{I, ag}) \sim 2.6 \times 10^{-4}$ and $f(\text{K, ag}) \sim 1.7 \times 10^{-3}$. This is favorable to be detected in nearby star forming regions[3].

DETECTABILITY

Numerical simulations[4, 5] suggest that collisions of the type we are discussing are plausible. The basic picture is that there are secular perturbations of the inner planets, which over time scales comparable to the age of the system lead to large changes in eccentricity and semi-major axis for one or more planets, leading to a large probability of collision.

The event rate can be roughly estimated. Assuming that on average a solar-system like our own has 5 collisions over its life time, and that essentially every star harbors a planetary system, the collision event rate in our galaxy would be about $5 \times 10^{11} / (10^{10} \text{ yr}) \sim 50/\text{yr}$.

Considering an ensemble of stars with an average age \bar{t} , in order to detect one event with duration τ after a continuous observation time of t_{obs} , the critical number of stars in this ensemble that have to be searched is

$$N_* = (f_p \bar{N}_c)^{-1} \frac{\bar{t}}{\max(\tau, t_{\text{obs}})}, \quad (4)$$

where $f_p \sim 100\%$ is the fraction of the stars in the ensemble that have planets, and $\bar{N}_c \sim 5$ is the average total number of collisions during the lifetime of a typical star in the ensemble. One can also define a characteristic flux $F_{v,c}$ of the collisional events. Given a number density n_* of the stars with the average age \bar{t} , one can estimate a critical distance one has to search in order to find one collisional event, i.e., $D_c \sim (N_*/n_*)^{1/3}$. The typical flux can be then estimated with D_c . Although N_* is sensitive to the average age \bar{t} of the ensemble of stars being investigated, D_c and $F_{v,c}$ are essentially independent of the ensemble adopted, given a constant birth rate of stars. According to such an estimate, the *Extreme Ultraviolet Explorer (EUVE)* all-sky survey[6] may have recorded ~ 10 such events, with the brightest one having a count rate of about $(170 - 680)$ counts ks^{-1} at 100 angstrom. The predicted flux level is also well above the sensitivity of soft X-ray detectors, such as *ROSAT*, *Chandra*, and *XMM-Newton*, so that there might be such events recorded in their archival data as well.

SEARCHING STRATEGY

A future dedicated wide field detector sensitive to (50-200) angstrom would be able to detect 10's of EUV-soft-X-ray flares per year due to planetary collisions. Photometrically monitoring a huge number of stars over a long period of time by missions such as *GAIA*[7] (or other synoptic all-sky surveys) for several years should lead to detections of several collisional events. If an EUV-soft-X-ray flare is detected, a search of its optical and radio counterpart (like catching afterglows in gamma-ray burst study) is desirable. A planetary-rotation-period modulated fading signal would be an important clue. Doppler radial velocity measurements and IR monitoring may be performed later for the collision candidate to verify the existence of the planet(s). Each collisional event would leave a bright remnant glowing in IR. The duration of the afterglow is thousands of years. Such afterglows could be directly searched in the nearby star forming regions, and the planets could be directly imaged.

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